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Observations of Running Waves in a Sunspot Chromosphere

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Abstract. Spectropolarimetric time series data of the primary spot of active region NOAA 9448 were obtained in the Si I 10827 Å line and the He I 10830 Å multiplet with the Tenerife Infrared Polarimeter. Throughout the time series the spectrograph slit was fixed over a region covering umbra, a light bridge, penumbra, and quiet sun. We present speeds of running penumbral waves in the chromosphere, their relation to both photospheric and chromospheric umbral oscillations, and their dependence on the magnetic field topology.

1. Introduction

Running penumbral waves (RPWs), which exist in sunspot chromospheres, were first observed by Zirin & Stein (1972) and more recently studied though various imaging observations (e.g., the series of papers by Christopoulou et al. 2000; Georgakilas et al. 2000; Christopoulou et al. 2001). Although this phenomenon has been investigated in detail, the origin of these moving disturbances and their relation to other phenomena occurring within sunspots remains unclear. In particular, a comparative study by Tziotziou et al. (2006) between the possibility of RPWs being a trans-sunspot wave in the chromosphere or a visual pattern of upward-propagating waves was unable to conclude one way or the other.

The work presented here will attempt to finally address the true origin of these waves using full Stokes observations of a sunspot obtained at high cadence. The benefit of observing the full Stokes polarization profiles is the retrieval of the complete magnetic field vector, circumventing the need for any assumptions of the field topology in our conclusions of possible wave propagation.

2. Observations

The data used here were obtained on 2001 May 9 with the Tenerife Infrared Polarimeter (Martínez Pillet et al. 1999) attached to the German VTT. The full Stokes (I, Q, U, V) vector was measured by a slit fixed across active region NOAA 9448. The slit sampled sunspot umbra, a light bridge, penumbra and neighbouring quiet Sun at a rate of one exposure every 2.1 s over the period 09:10-10:20 UT. The recorded data from inside the sunspot umbra were previously presented by Centeno et al. (2006), who found vertically propagating, slow-mode waves in a stratified isothermal atmosphere to reliably fit the observed temporal Fourier behaviour when radiative cooling was taken into account.

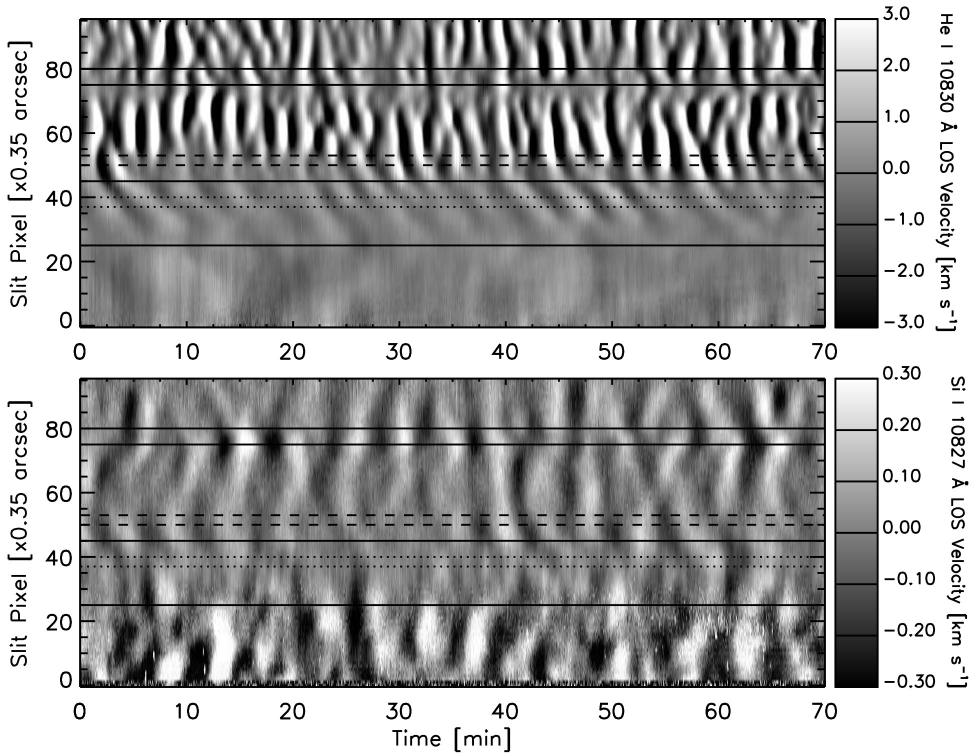

Figure 1. Space-time plots of LOS velocity in the photospheric Si I 10827 Å line (*bottom*) and upper-chromospheric He I 10830 Å multiplet (*top*).

The Stokes profiles of the photospheric Si I 10827 Å and high-chromospheric He I 10830 Å lines were individually inverted using the inversion code of Lagg et al. (2004). Atmospheres containing a single magnetic component were used in both cases, while the Si I inversion included an additional non-magnetic, stray-light component. The resulting line-of-sight (LOS) velocities from the inversion are displayed in Figure 1, where solid horizontal lines mark boundaries between different regions of the sunspot: quiet Sun ($y \approx 0-25$); penumbra ($y \approx 25-45/50$); umbra ($y \approx 45/50-95$); a light bridge ($y \approx 75-80$). It is evident that whereas the umbral oscillations in He I have a period of 3 min, in Si I the umbra oscillates at around 5 min. Note, the RPWs also show a period close to 5 min.

3. Horizontal Motions

Initially, raw He I velocities were studied to determine the apparent horizontal propagation speed of the RPW disturbances through the penumbra. Simple spatial tracking of a number of the velocity maxima in Figure 2*a* yielded values $\sim$16 km s^{-1}. Time lags between all of the penumbral He I velocity signals and an averaged, mid-penumbral He I signal (region of averaging marked by dotted lines in Fig. 1) were found by cross-correlating the velocity profiles in time and are presented in Figure 2*b*. Spatial tracking of the peak correlation yielded an apparent speed of $\sim$18 km s^{-1}. The same spatial correlation approach was also

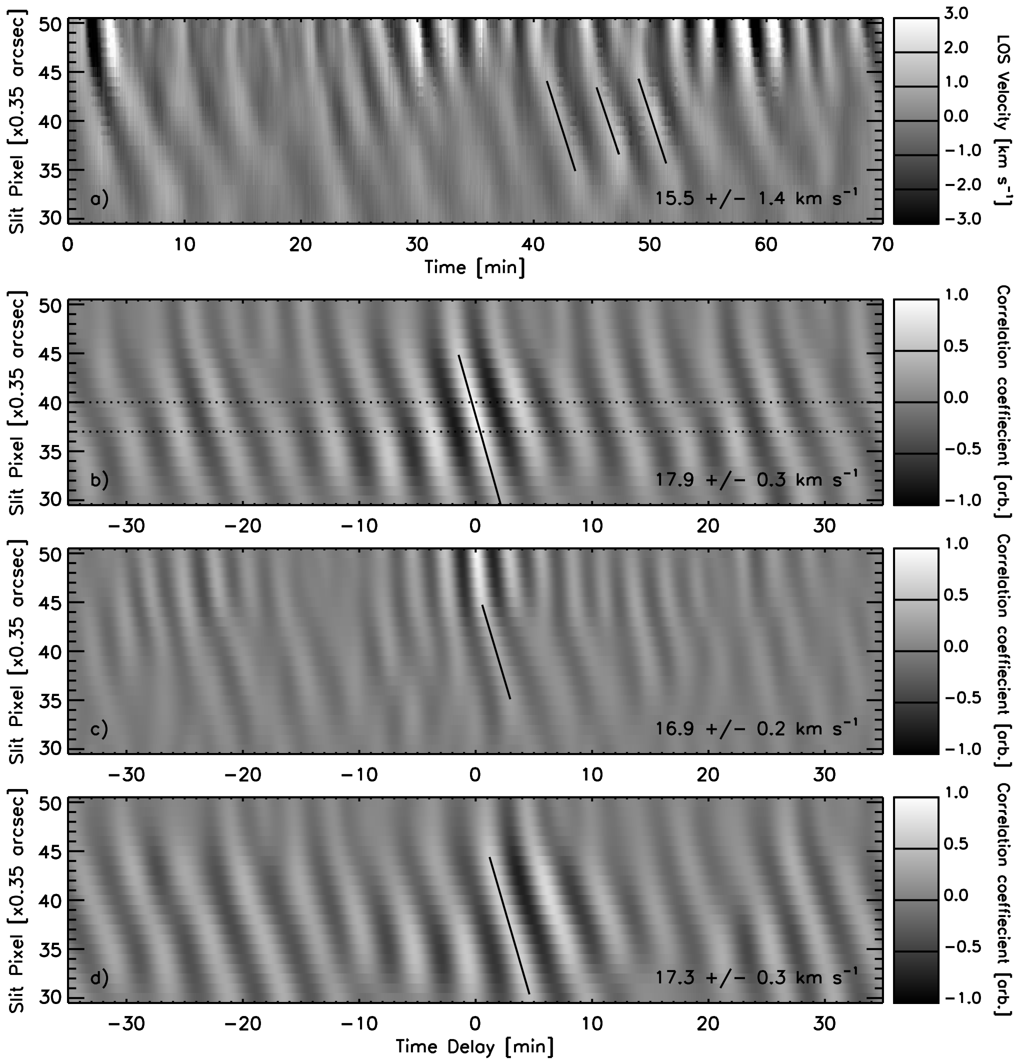

Figure 2. *a*) Space-time plot of penumbral LOS velocity in the He I multiplet. Variation of temporal cross correlation between individual spatial He I velocity profiles and *b*) an average, central penumbral He I profile, *c*) an average, outer umbral He I profile, and *d*) an average, outer umbral Si I profile.

performed between all of the penumbral He I velocity signals and both an averaged, outer-umbral He I signal (Fig. 2*c*; region of averaging marked by dashed lines in Fig. 1) and an averaged, outer-umbral Si I signal (Fig. 2*d*), each yielding apparent speeds of $\sim$17 km s^{-1}. These values are in good agreement with the previous literature (see, e.g., the recent review of Bogdan & Judge 2006). Note that values of correlation coefficient in the umbral He I case diminish rapidly through the penumbra since attempting to correlate a signal with a dominant 3–min period to one with a 5–min period. The correlation with the umbral Si I displays the opposite behaviour, being strong throughout the penumbra but petering out at the umbra/penumbra boundary for the same reason.

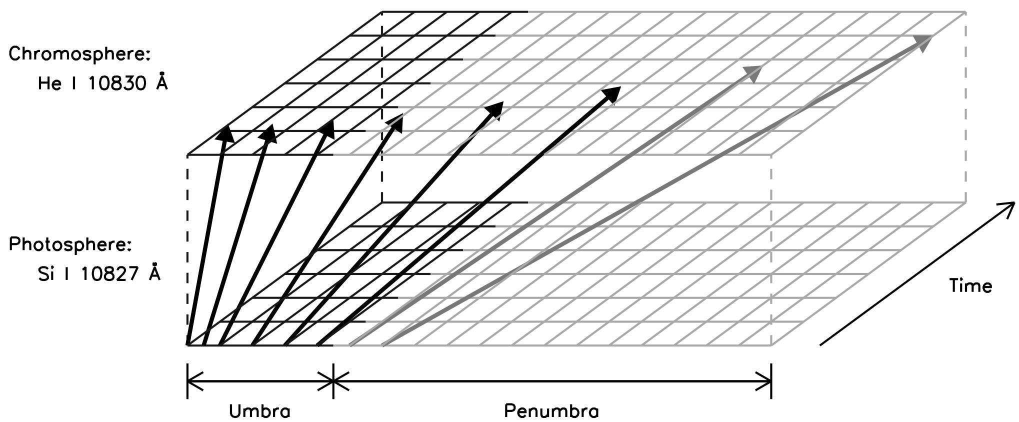

Figure 3. Cartoon schematic of the proposed field geometry linking pixels in the umbra (dark grid) to those in the penumbra (light grid) at photospheric and chromospheric sampling heights through increasingly inclined field lines.

4. Upward Propagation

The scenario proposed here for the generation of these running disturbances in the penumbral chromosphere is shown in Figure 3 as a cartoon schematic. Although assuming vertical fields in the umbra of this sunspot was sufficient for the work of Centeno et al. (2006), pixels toward the outer edge of the umbra show somewhat inclined fields ($35 - 45°$; which may account for the spread of phase difference points with frequency in Centeno et al. 2006). These inclinations mean that some field lines originating from the photospheric umbra can pass through the chromospheric penumbra. From the values of inclination retrieved here, most chromospheric penumbral pixels can be traced back to the outer umbra/inner penumbra, all of which show photospheric velocity signatures of similar phase. If waves which travel along the field are indeed excited at the photospheric level within the umbral region (as shown by Centeno et al. 2006), those waves propagating along more inclined paths will have larger distances to traverse before showing their presence at the He I sampling height in the upper chromosphere. The increased path lengths that are experienced with increasing distance through the chromospheric penumbra mean that initially similarvelocity signals in the Si I line have increasing temporal delay in the He I signal, resulting in an apparent horizontal motion outward from the umbra as proposed by Rouppe van der Voort et al. (2003).

Photospheric and chromospheric spatial pixels were paired using the values of local solar inclination recorded in the Si I and He I lines to determine the expected spatial offset between the two sampling heights in the atmosphere. The subsequent LOS velocity pairings between the photosphere and chromosphere were subjected to Fourier phase difference analysis following Krijger et al. (2001). Phase difference spectra from several neighbouring spatial pixels were overplotted in each of the panels of Figure 4 to heighten the clarity of any relation which may exist. These phase difference diagrams are comparable to Fig. 6 of Centeno et al. (2006), although they differ slightly as the shade and size of data points here denote the Fourier coherence and cross-spectral power, respectively.

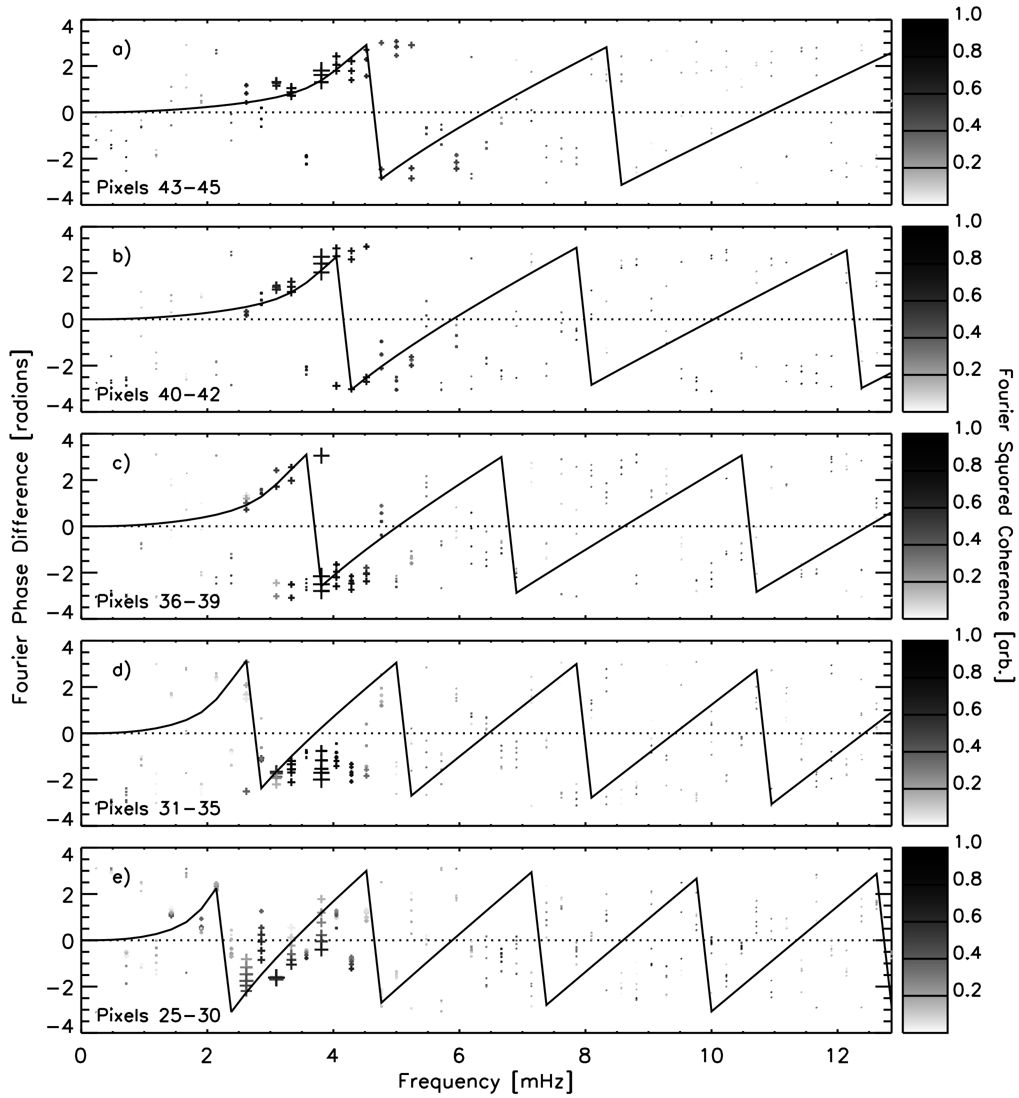

Figure 4. Phase differences between spatially offset pairings of photospheric and chromospheric LOS velocities. Panels show phase difference relations moving from those chromospheric pixels closest to the umbra/penumbra boundary (*top*) toward those at the penumbra/quiet-sun boundary (*bottom*).

It is clear when moving from the chromospheric umbra/penumbra boundary (top panel) toward the penumbra/quiet sun boundary (bottom panel) that the phase difference relations show deviation from the classical acoustic cut-off (∼5.2 mHz) which can be explained by the reduced gravity experienced by waves propagating non-vertically. Solid curves plotted in Figure 4 show the expected phase difference relations achieved using the equations provided by Centeno et al. (2006) for field-aligned waves in an isothermal atmosphere with radiative cooling, when the reduced gravity and increased path length from inclinated fields are taken into account, and the values of temperature, height separation, and cooling time scale which they determined for the umbra of this sunspot ($T = 4000$ K, $\Delta z = 1000$ km, and $\tau_R = 55$ s, respectively). Although only arbitrarily chosen and not reached by any form of fitting, good comparison is found with the observations for field inclinations of 40°, 45°, 53°, 63°, and 65° when moving from top to bottom panels of Figure 4: these values are in good agreement with the solar inclinations determined by the Stokes inversion.

5. Future Work

Given that the work presented here is incomplete, the initial results are very promising. Fourier analysis confirms that RPWs are indeed the visual pattern of slow-mode magnetoacoustic waves that are generated at very similar phase at the photosphere but propagate along field lines of increasing inclination, hence showing increased time delays at (roughly) the same chromospheric altitude.

Improvements that are still required include least-squares fitting of the phase difference relation to the data to retrieve the spatial variation of the physical parameters T, Δz, and τ_R. In addition, refinement of the Si I inversion to include fine structure in the photospheric penumbra (e.g., a second magnetic component to account for known highly inclined filament or flux tube fields) will provide better linkage between velocity signals in the inner-penumbral photosphere and those in the outer-penumbral chromosphere. Observations of a small pore region will also be investigated for such running waves since the findings of this work indicate that the existence of a penumbra is not neccessary for their production: only sufficiently inclined fields in the umbra (or pore) are required to guide the waves outside this region.

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